AN AID FOR FORECASTING THE MINIMUM TEMPERATURE AT DENVER, COLO.

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[Manuscript received July 14, 1952; revised manuscript received August 10, 1953]

ABSTRACT

Research on objective forecasting of minimum temperatures is reviewed and the general approach to the problem at Denver is discussed. The variables selected and the graphical combination of these variables are described in detail. Results of forecasts made by exclusive use of the aid are presented and a comparison is made between these forecasts and the official minimum temperature forecasts issued to the public. It is found that the "system" forecasts compare very favorably with the official forecasts and the conclusion is drawn that with continued use of the aid and greater familiarity with its shortcomings the forecasters will be able to consistently improve upon the forecasts produced by the aid and in the long run improve the overall skill in forecasting the minimum temperature for Denver.

INTRODUCTION

A number of articles have appeared in the meteorological literature in recent years on objective methods of forecasting various weather elements. Few of these studies have shown any significant improvement over official forecasts made from the same data. This is not surprising since most of these studies have been based on the experience of forecasters at a particular location with the particular weather element, and no new concept or better understanding of the atmospheric processes has been introduced. (The present study is no exception in this respect.) On the other hand, most of these studies have shown that *equal* results or skills are attainable through relatively simple, objective, *quantitative* procedures. It appears that most of our knowledge of forecasting of a particular weather element for a certain place can be boiled down to a few variables and put on a quantitative basis. It is in the word "most" that the forecaster still has the edge on an objective system. Since equal or almost equal skill is incorporated in the objective system it behooves the forecaster to know what answer it gives, know what has gone into it, and then consider the current synoptic situation from the standpoint of the unusual in the situation that the objective method has not considered, and possibly could not consider. This would relegate the objective "system" or "method" to the position of an "aid" to the forecaster where it belongs. In using such an aid it is important that the forecaster record all occasions on which he differs with the aid appreciably so that over a period of time he can determine whether, on the average, he is improving the forecasts by changing them.

In this study an attempt was made to systematize and put on a quantitative basis the main factors used by experienced forecasters for forecasting the daily minimum temperature at Denver, Colo. The minimum temperature forecast chosen was the one made in the morning at around 0800 MST at Denver based on the 1230 GMT (0530 MST) surface and related charts. This forecast is for the following night and constitutes a 12—24-hour forecast depending upon the time of occurrence of the minimum temperature. Normally it amounts to a 24-hour forecast since the minimum temperature usually occurs around 0530 MST.

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Surprisingly few articles have been written on what would seem to be one of the important subjects in day-to-day forecasting. A minimum temperature forecast appears in almost every general forecast written today whether it is for a specific locality or for a large area such as a State. Those text books on meteorology and forecasting which even mention minimum temperature confine the discussion to those factors which affect the minimum temperature at a point and introduce such wide variability in minimum temperatures within the same air mass. These factors will be discussed in a section below under Sources of Error.

Rules for use of the 12-hour sea level pressure change chart in forecasting temperature trends 24 to 48 hours in advance have been formulated or compiled by several experienced forecasters such as Cook [1], Lloyd [2] and others. But the determining of the estimate of the actual minimum temperature for a given locality is left to the experience of the forecaster for that locality.

Objective methods of temperature forecasting have been used for many years in the "fruit-frost" protection service in California and other States. In this type of work forecasts are for a short period, the forecast being made in the late afternoon or evening for the minimum temperature occurring the same night or following morning. The time lag is at most 12 hours. The forecast is based chiefly on the effect that moisture in the lowest layers of air has on nighttime radiation. When the time lag of the forecast is extended to 24 hours or longer the effect of air movement becomes much more important. The forecast problem then becomes primarily that of locating on this morning's weather map the source of air which will be over the station tomorrow morning.

One of the first attempts to put 24-hour minimum temperature forecasting for a locality on an objective basis was by Wilson [3] for Washington, D. C. His technique required the selection each day of an index station located upwind from Washington at a distance equivalent to 24 hours of air flow on the 10,000-foot chart. The surface temperature at this station was then used in a simple linear regression formula to obtain the forecast minimum temperature for Washington. Later Brier [4] showed that comparable results could be obtained from a least-squares equation relating the 0130 EST temperature at Columbus, Ohio, to the temperature at Washington 30 hours later.

Further research in developing objective methods of forecasting the minimum temperature was done in 1945 at New York University sponsored by the Weather Bureau. The first report on this research made by Miller and Burgtorf [5] described a method of estimating the mean seasonal origin of air coming into New York City. For each season of the year a fixed station upstream was selected as the mean seasonal origin and a relationship was shown to exist between the minimum temperature at this fixed station and the subsequent minimum temperature at New York City the following morning. This research was later supported by the U. S. Army Air Forces and in a second report issued by the Air Forces Weather Station at New York University (Mantis and Dickey [6]), a method was outlined for forecasting the daily 24-hour surface air trajectory into New York, thus varying the index station from day to day. In 1947 Mook and Price [7] of the Weather Bureau applied the Trajectory Method to Washington, D. C., and conducted additional studies directed toward refinements of these methods.

In 1949 Dickey [8] developed an objective system for estimating the probability of a large fall in temperature 30 hours in advance for Washington, D. C., and in another report [9] applied similar criteria to Philadelphia to forecast the daily minimum temperature. Hardy [10] in 1951 applied the Philadelphia method with certain refinements to New York City.

GENERAL APPROACH TO THE DENVER PROBLEM

The basic approach underlying all of the above-mentioned studies is the attempt to determine the source of air expected over the station at verification time and establish relationships between temperatures in this air at forecast time with the subsequent minimum temperature at the station. This, of course, is the basic and logical approach to all longer range temperature forecasting, subjective or objective, for locations in relatively flat country. A barrier such as the Rocky Mountains with elevations 5,000 to 9,000 feet higher than the station, immediately to the west and extending for several hundred miles north and south introduces complications to such an approach. Any attempt to construct surface air trajectories from pressure patterns would be useless. Such trajectories, if constructed, would be extremely fictitious. Representative temperatures in the air mass expected to be over Denver do show a good relationship with the Denver minimum temperature, however, when the air mass is a cold outbreak from the north or northwest and on a few occasions from the northeast. In such cases there is a definite progression, or advection, of cold air over the entire region and temperatures behind the cold front show a definite relationship to Denver's minimum temperature. As the cold air pushes southward, however, and engulfs New Mexico, Kansas, and Texas, the reaction to warmer temperatures takes place to the north of Denver first and progresses southward. This warming is accompanied, or caused, by the development of a "lee trough" east of the mountains. The warmer temperatures then cannot be attributed to advection of warmer air from the south but must be accounted for by insolation and dynamic heating and warm air advection aloft from the northwest. For this reason temperatures to the north were found to be more highly correlated with the subsequent minimum temperature at Denver than those to the south or southeast when the surface pressure pattern at forecast time might indicate that the air flow into Denver was from the southeast.

Similarly when a trough or low pressure system moves in off the Pacific to the west or southwest of Denver the southwest flow normally expected ahead of such a trough is blocked in the lower levels by the mountain ranges, and as a consequence surface temperatures "upstream" to the southwest of Denver show very little relationship to the Denver minimum temperature. In such cases, also, temperatures to the north and northwest of Denver were found to be related to the minimum temperature at Denver.

The sea level pressure distribution, the changes in pressure as reflected on the 12-hour pressure change chart, and the movement of the pressure change centers are used extensively at Denver to forecast temperature trend. The general approach to the minimum temperature forecast problem for Denver, then, was to establish a trend forecast from sea level pressure and pressure change variables and then investigate temperature variables both at the surface and at 700 mb. for estimating the actual minimum temperature. The search for temperature variables related to Denver's minimum was guided by the considerations discussed above.

VARIABLES INVESTIGATED

TREND FORECAST

Experience in forecasting temperatures and temperature changes at Denver has established association of certain pressure distributions or patterns with subsequent temperature trends. One such pattern which indicates a trend toward warmer temperatures is the existence and intensification of a "plateau" or "Great Basin" High centered over the plateau region west of the Continental Divide. A measure of the existence of such a High cell is the current sea level pressure at Grand Junction, Colo. (Any other station west of the Divide would probably work almost as well.) Grand Junction was chosen as a result of preparing two composite 0530 MST sea level pressure charts for cases in which the minimum temperature at Denver 24 hours later was 10° F. or more below normal and 10° or more above normal. The greatest pressure difference between these two charts was located at Grand Junction. The intensification, or dissipation, of the High is reflected in the 12-hour pressure change at Grand Junction. The intensification of the High is usually accompanied by the development of a trough to the east of the Divide creating a strong west-to-east pressure gradient which results in down-slope winds in the Denver area and dynamic warming. The development of this trough is preceded by 12-hour pressure falls to the north of Denver, east of the Divide.

The pattern most generally associated with a trend toward colder temperatures 24-hours in advance is the existence of low pressure over the plateau region, somewhat to the south of Denver, and high pressure with cold temperatures to the north. Rising pressure to the north and falling pressure to the west or southwest of Denver are indicative that the cold air will push southward east of the Divide and engulf Denver. The current (0530 MST) pressure at Grand Junction again indicates the existence of low pressure west of Denver and the 12-hour pressure change at the same station accompanied by a pressure rise to the north indicates the movement of colder air southward. The station to the north selected for measuring the 12-hour pressure change was Sheridan, Wyo. This station was selected again on the experience of forecasters for this region as being a somewhat greater distance from Denver than the average 24-hour movement of cold air from the north, and thus is in general behind the cold front advancing southward in such situations.

Temperatures have a decided tendency to regress toward the normal when extreme values are reached. Or in other words, if the temperature one morning is considerably below normal, the probability that the temperature the following morning will be higher is greater than that it will be lower. This concept in itself would suggest that the daily departure from normal be used as a variable in predicting trend. If the normal minimum temperature varied greatly during the season being investigated, or if the study were made on a yearly basis, the departure would be the logical variable to use. The normal minimum temperature at Denver during winter varies from 15° to 28° F., but since the tendency for regression toward normal is most pronounced when the departures from normal are most extreme, the observed minimum itself was considered a sufficient measure of its abnormality. However, before making the final decision on this variable, the departure from normal was tried instead of the temperature itself. Little difference was shown so the current minimum was used.

To summarize the above discussion, the following variables were used to determine a trend forecast:

1. Current minimum temperature. This is the minimum temperature that has occurred during the night up to 0530 MST.
2. The 0530 MST sea level pressure at Grand Junction, Colo.
3. The 12-hour pressure change at Grand Junction, Colo. (1730 to 0530 MST) corrected for diurnal tendency.
4. The 12-hour pressure change at Sheridan, Wyo., also corrected for diurnal tendency.

These four variables were combined graphically to arrive

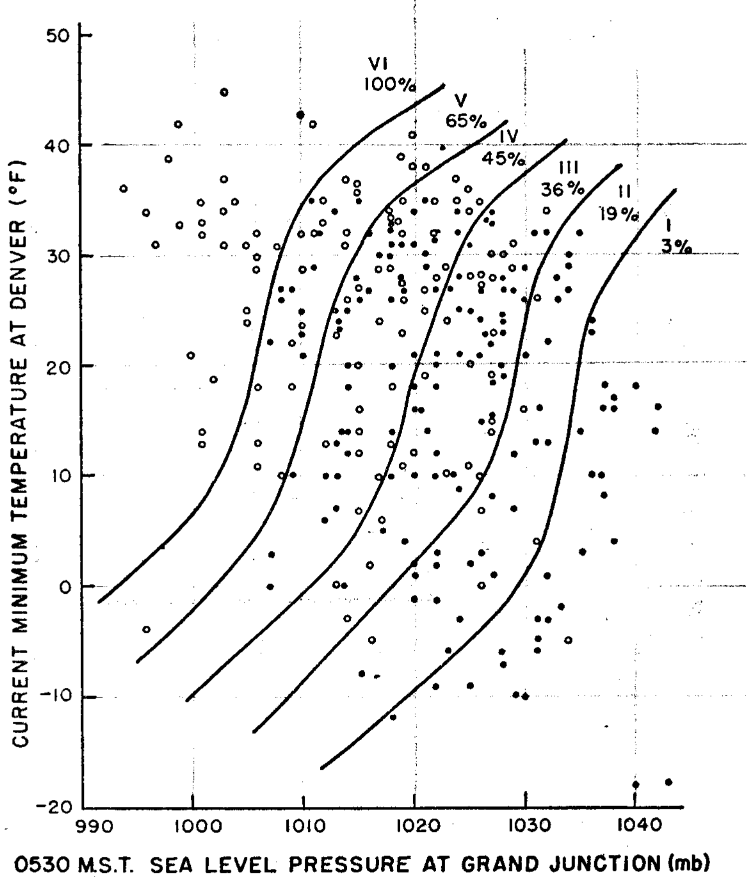

FIGURE 1.—Joint relationship between the current minimum temperature at Denver, the 0530 MST sea level pressure at Grand Junction, and the subsequent change in the Denver minimum temperature. The probability of a *fall* in temperature is indicated for each numbered area. An open circle indicates a fall in temperature and a dot indicates a rise or no change in temperature.

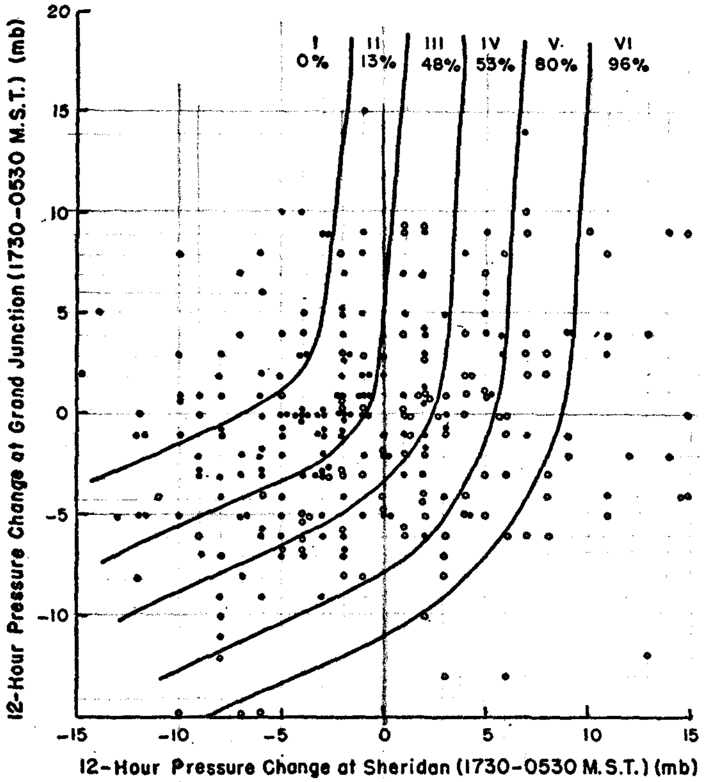

FIGURE 2.—Joint relationship between the 12-hour pressure change at Grand Junction, Colo., the 12-hour pressure change at Sheridan, Wyo., and the subsequent change in minimum temperature at Denver. The probability of a *fall* in temperature is indicated for each numbered area. An open circle indicates a fall in temperature and a dot indicates a rise or no change in temperature.

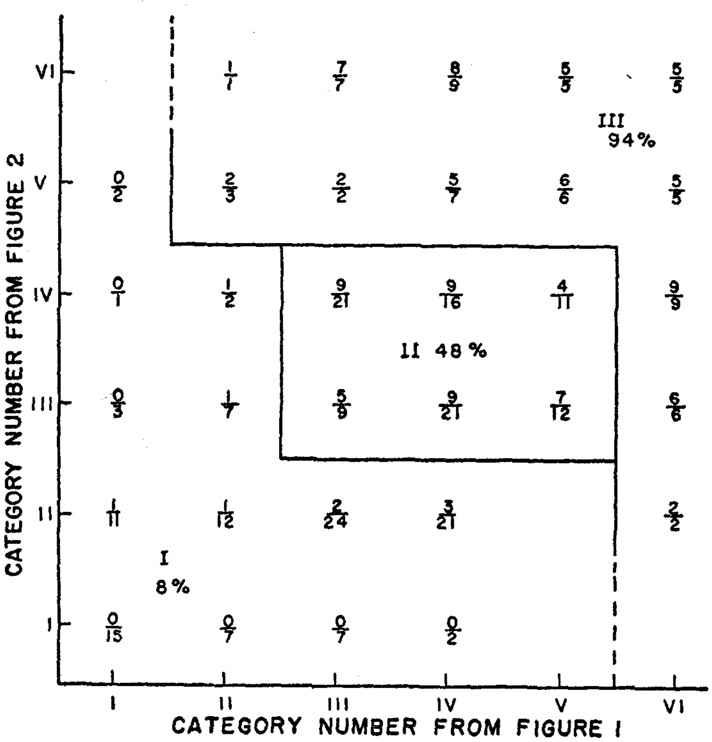

FIGURE 3.—Joint relationship between the probabilities of a fall in temperature from figures 1 and 2 (as expressed by the category numbers) and the change in minimum temperature. The denominator of the fraction at each point is the total number of cases and the numerator is the number of cases with falls in temperature.

at a *trend forecast*. The analysis used actually gives the probability of the trend rather than a yes or no answer that warmer or colder will result. It was found later, however, as might be expected, that the probability of trend was related strongly to the average change in minimum temperature.

The current minimum temperature at Denver and the 0530 MST sea level pressure at Grand Junction were paired and used as coordinates of a scatter diagram on which was plotted the subsequent change in the minimum temperature, a positive value indicating warming and a negative value cooling. The temperature change was plotted on the chart as a circle or a dot, the circle indicating a temperature fall and the dot a temperature rise or no change. Areas containing approximately equal numbers of cases were delineated on this chart and then the ratio of the number of temperature falls to the total number of cases in each area was determined. This ratio was expressed as a percentage and entered on the chart at the center of the area. On the basis of these percentages, the chart was then divided into six elongated areas or channels in which the percentage of occurrence (or probability of occurrence) of a fall in temperature progressively increases across the chart (fig. 1). The areas of probability were labeled with category numbers from I to VI, the area of lowest probability being designated category I.

The 12-hour pressure changes at Grand Junction and Sheridan were used as coordinates of a second scatter diagram with the change in minimum temperature again plotted on the chart as a circle or a dot (fig. 2). The same type of analysis was made on this chart as described above.

For each case category numbers were determined from figures 1 and 2. These category numbers were then used as coordinates of a third chart. For each combination of category numbers the total number of cases and the number of temperature falls were tabulated. These numbers were entered at the point determined by each combination of category numbers, the denominator being the total cases and the numerator the number of temperature falls (fig. 3). The chart was then divided into three areas, one in which falls in temperature predominate, one in which rises in temperature predominate, and the third in which an approximately equal number of rises and falls occur. In area I of figure 3 the probability of a fall in temperature is only 8 percent, or the probability of a rise or no change is 92 percent. In area II the probability of a rise or fall is approximately 50 percent, and in area III the probability of a fall in temperature is 94 percent.

ESTIMATING THE ACTUAL MINIMUM TEMPERATURE

The first approach to estimating the actual minimum temperature was to treat the three groups delineated on figure 3 separately and a complete system was developed on that basis. However, it turned out that the same variables gave best results in all three groups and the analyzed charts showed so much similarity that the three groups were combined into the same charts, thus requiring only three charts for the forecast instead of nine (three for each group). The trend indication from figure 3 was retained, however, to evaluate some of the variables.

There are two main factors which determine the magnitude of the minimum temperature at a station. These are the temperature "this morning" of the air mass expected over the station "tomorrow morning," and the modification this air mass will undergo in reaching the station. There are other factors, such as snow cover, wind, and the presence or absence of clouds, which affect the final temperature reading and which will be discussed more fully under Sources of Error, but the major portion of temperature change is accounted for by the two factors mentioned. The following variables were used to measure the effects of these two factors:

1. *The Maximum Temperature at Denver "Today."* This variable is an indirect measure of the temperature of the surface of the ground over which the new air mass will pass and thus is a measure of the modification the air mass will undergo in reaching the station. Cook [11] has shown there is a very high degree of correlation between the afternoon maximum and the succeeding night time minimum on clear, relatively calm nights. While the variance is no doubt considerably larger when all days are considered, the correlation is still sufficiently strong to make the maximum temperature a very good forecasting variable for the minimum temperature. In order to use this variable in an early morning forecast a forecast of the maximum temperature for "today" obviously has to be made. The average error of the official forecasts of "today's" maximum temperature is relatively small, sufficiently small in fact, that there is very little difference between the correlation of the observed maximum and subsequent observed minimum and the correlation of the forecast maximum with the subsequent observed minimum. (These correlations are: observed maximum *vs.* observed minimum .87; and forecast maximum *vs.* observed minimum .85.) Furthermore, the technique of forecasting the maximum temperature "today" is fairly uniform among forecasters. The observed maximum was therefore used in constructing the charts. This variable was used in all three trend groups from figure 3.

2. *Temperature at Surface Index Station.* As stated above under General Approach, in only one group of cases, where a cold air mass is moving down from Canada, does the surface temperature at the index station chosen represent the temperature of the *air mass* which will be over Denver at verification time. This is essentially Group III and part of Group II from the trend chart, figure 3. In the rising temperature cases, Group I and part of Group II of figure 3, the temperature at the index

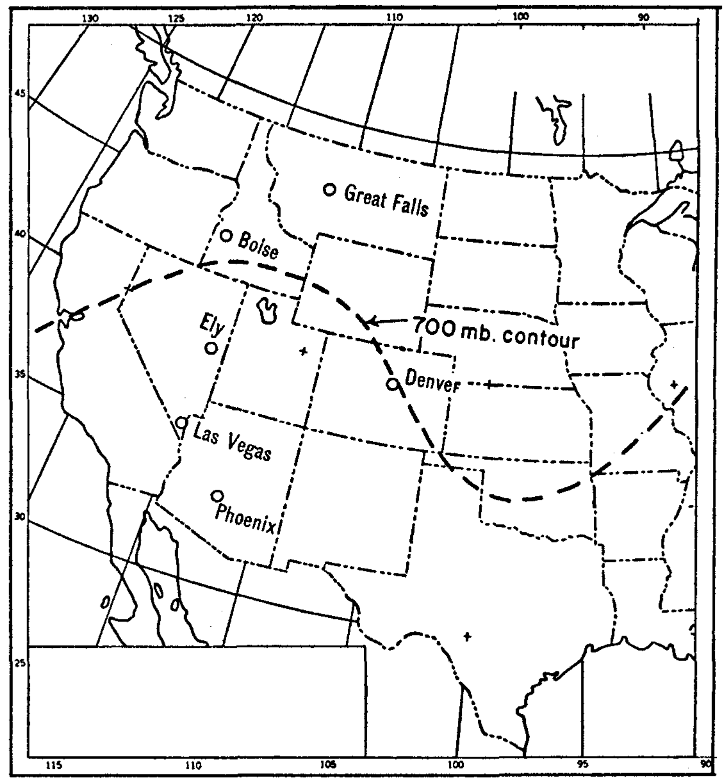

FIGURE 4.—Location of raob stations used in selecting the 700-mb. index temperature.

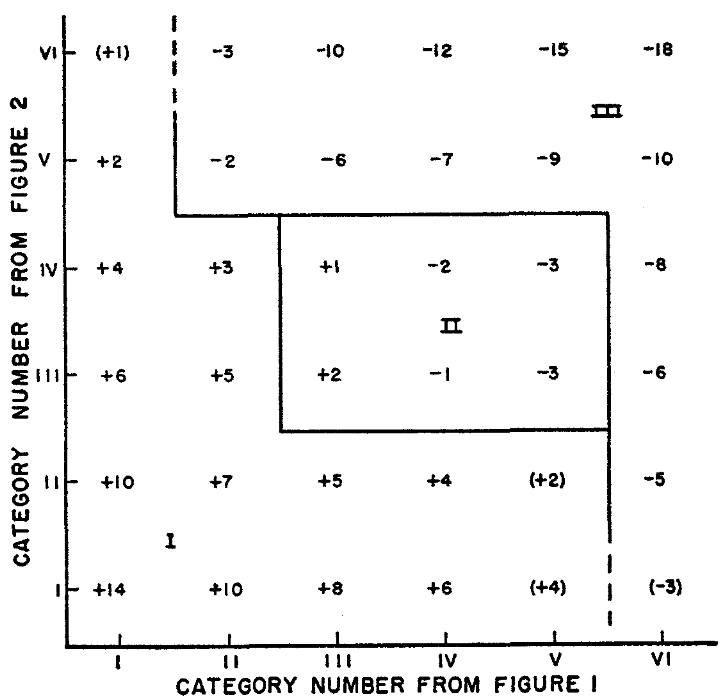

FIGURE 5.—Joint relationship between the probabilities of a fall in temperature from figures 1 and 2 (as expressed by the category numbers) and the average change in the minimum temperature. The number plotted at each point is the average change (° F.) for all cases falling at that point. A positive value indicates a rise in temperature, a negative value a fall in temperature. Numbers in parentheses were entered arbitrarily to fill out the chart and are not based on data.

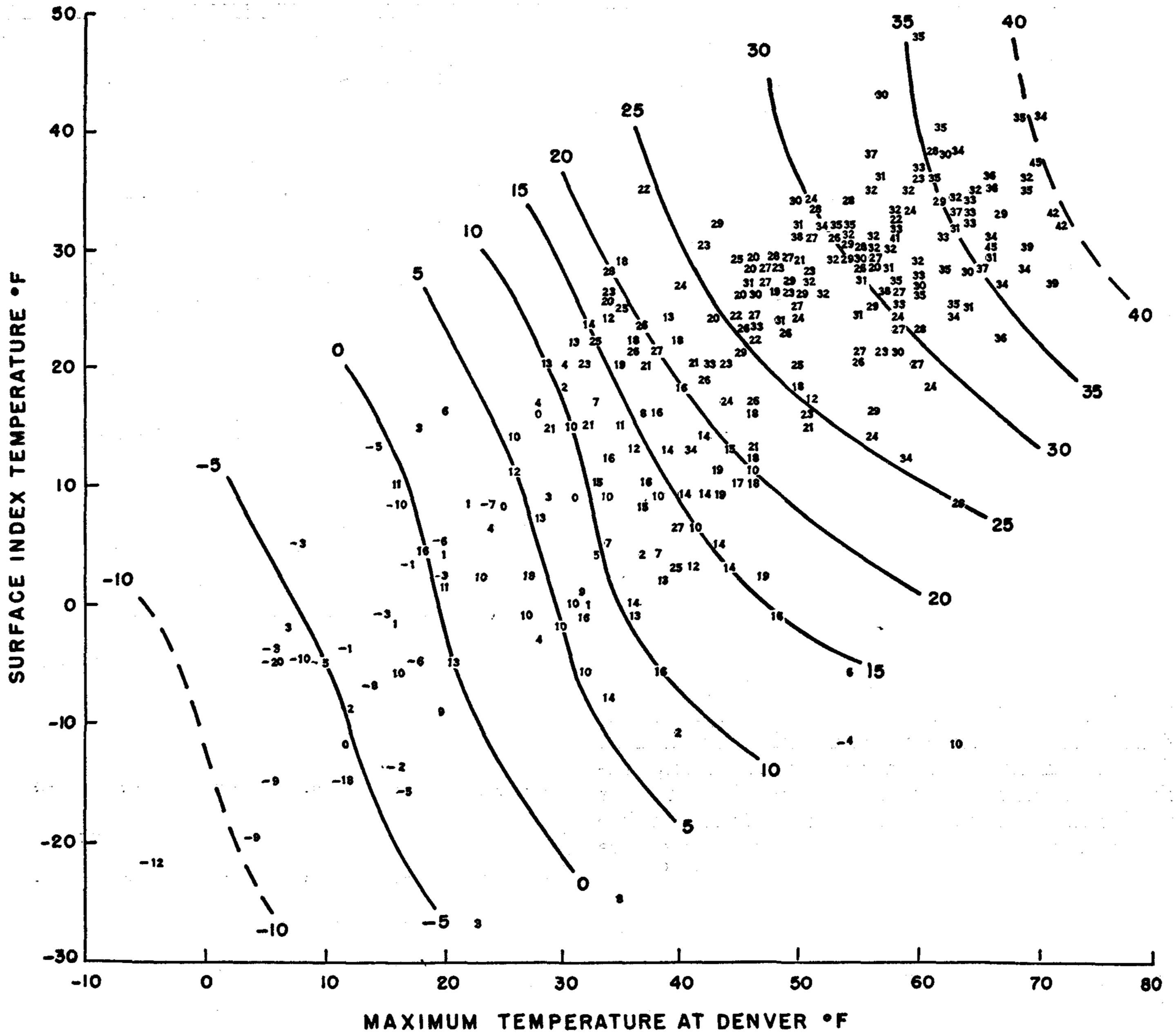

FIGURE 6.—Joint relationship between the maximum temperature at Denver, the minimum temperature at the surface index station, and the subsequent minimum temperature at Denver. Lines are isograms of minimum temperature (° F.) fitted to computed average values over the chart.

station does not represent the air that will be over Denver, but indicates the magnitude of temperature which can be expected at Denver 24 hours later due to similar dynamic heating effects. Fortunately, the same index stations could be chosen to represent both of these effects. The stations chosen were Sheridan, Wyo., and Pocatello, Idaho. Sheridan alone was used at first, but it was found from inspecting some of the larger errors that often a cold air mass approaching from the northwest would not have reached Sheridan by 0530 MST and thus a station west of the Divide would be more representative of the air. Similarly when a warming trend was indicated, the reaction to warmer often had not taken place at Sheridan yet but had west of the Divide. The following scheme was evolved, therefore, for choosing the index station: If the case fell in Group I (warmer) of figure 3, the warmer of Sheridan or Pocatello was used; if the case fell in Group III (colder), the colder of Sheridan or Pocatello was used; and if the case fell in Group II the average of the two stations was used.

3. The 700-mb. Index Temperature. For a further indication of the temperature of the air mass expected over Denver at verification time, a simple measure of advection at 700 mb. was employed. This measure of advection is illustrated in figure 4. The contour line through Denver on the 2000 MST 700-mb. chart was traced upstream until it passed between two of the radiosonde stations indicated in figure 4. The 700-mb. temperature employed was then again based upon the trend indications of figure 3. If the case fell in Group I, the temperature at the more southerly of the two stations between which the contour line passed was used; if the case fell in Group III, the temperature at the more northerly station was used; and if the case fell in Group II, the average of the two stations was used. If the contour passed east of Great Falls, the temperature at Great Falls was used in all cases, or if it passed east of Phoenix in a southerly flow, the temperature at Phoenix was used. When the contour through Denver was closed, Boise, Idaho was arbitrarily chosen as the index station. This assumes eastward movement of the closed system and subsequent advection of air from the northwest.

4. Average Change as Indicated by the Trend Forecast Variables. A fourth variable makes use of the pressure variables used in the trend forecast to arrive at an estimate of the actual minimum temperature. Figure 3 was reanalyzed and the average change in the minimum temperature was computed for each point determined by the category numbers from figures 1 and 2 instead of the probability of a fall in temperature. The resulting chart is shown in figure 5. The changes progress rather uniformly from large positive values (warmer) in the lower left section of the chart to large negative values (colder) in the upper right section of the chart. (The four numbers in parenthesis on this chart were entered arbitrarily to fill out the chart and are not based on data.) Comparison of figure 5 with figure 3 shows a high degree of association between the probability of change in temperature and the average change. The average change determined from figure 5 for any particular day was added to the current minimum temperature to obtain an estimate of the minimum which would occur the following morning. This estimate was used as an additional variable to combine with the others discussed above to arrive at the final forecast of the minimum temperature.

To summarize, the following variables were utilized to forecast the actual minimum temperature:

1. "Today's" maximum temperature.
2. Minimum temperature at Sheridan or Pocatello, depending upon the trend indication of figure 3:
   Group I—the warmer of Sheridan or Pocatello
   Group II—the average of Sheridan and Pocatello
   Group III—the colder of Sheridan or Pocatello
3. The 700-mb. Index Temperature: This temperature is obtained by tracing the 700-mb. contour through Denver upstream until it passes between two of the stations indicated in figure 4. The index station chosen depends on the trend indication of figure 3, as follows:
   Group I—the more southerly of the two stations is used.
   Group II—the average of the two stations is used.
   Group III—the more northerly of the two stations is used.
   Exceptions: When the contour passes to the east of Great Falls, the Great Falls temperature is used in all groups. When the contour passes to the east of Phoenix, the Phoenix temperature is used in all groups. If the contour is closed, in a closed Low, the temperature at Boise is used.
4. Average change as determined from figure 5 plus the current minimum temperature.

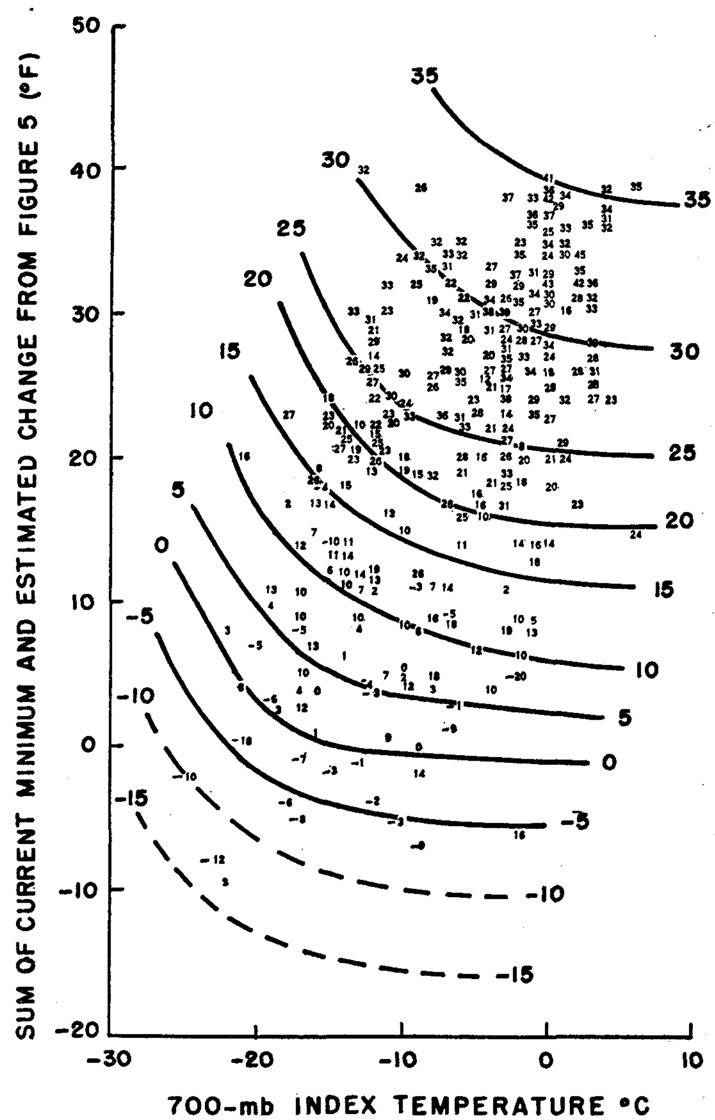

Figure 7.—Joint relationship between the 700-mb. index temperature, the sum of the current Denver minimum temperature and the average change from figure 5, and the subsequent minimum temperature at Denver. Lines are isograms of minimum temperature (° F.) fitted to computed average values over the chart.

COMBINING THE TEMPERATURE VARIABLES

The four temperature variables were combined and related to the subsequent minimum temperature by graphical techniques. The surface index temperature and

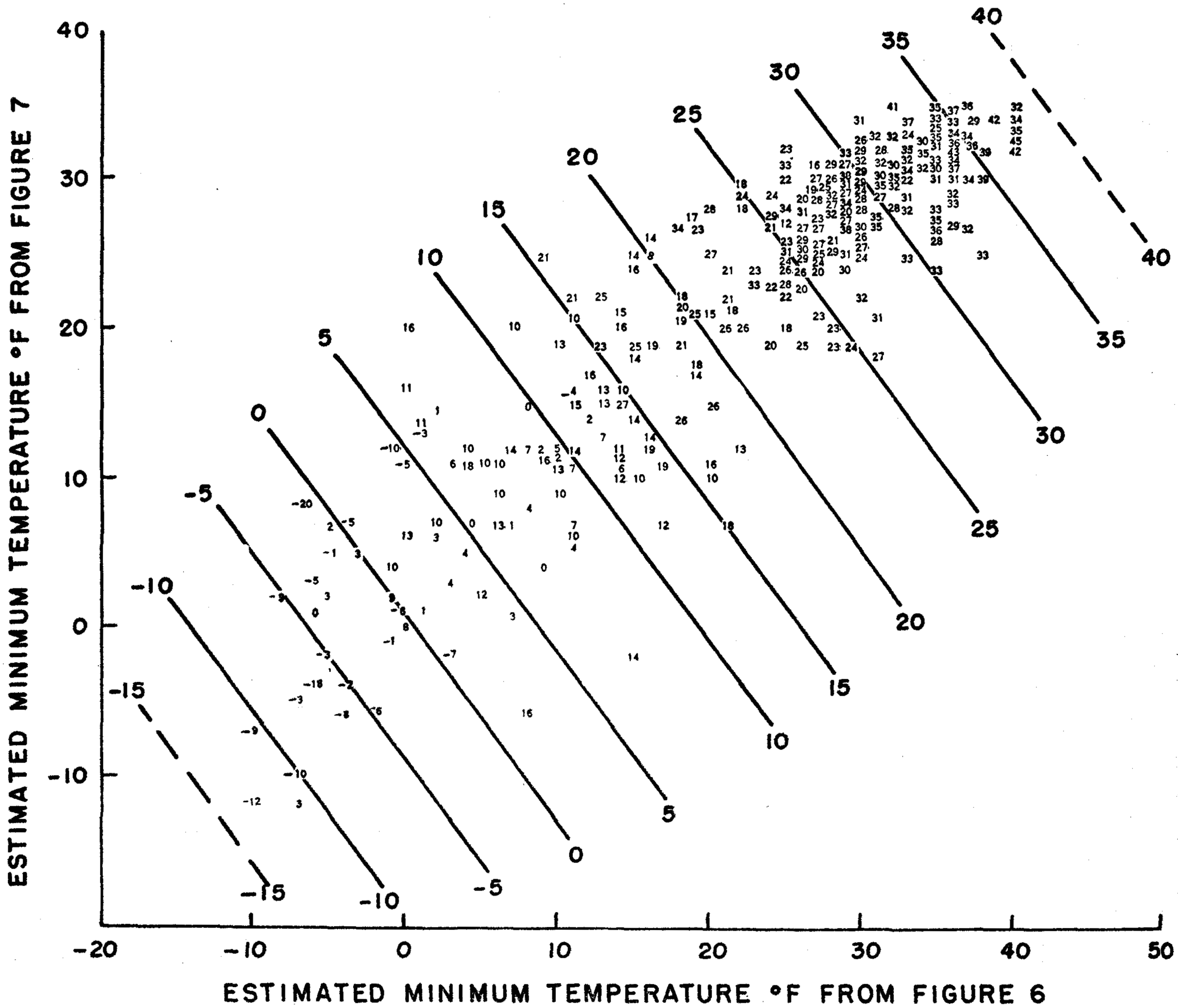

FIGURE 8.—Joint relationship between minimum temperature estimates from figures 6 and 7 and the subsequent minimum temperature at Denver. Lines are isograms of minimum temperature (° F.) fitted to computed average values over the chart.

the maximum temperature were paired and used as coordinates of a scatter diagram with the observed minimum temperature plotted at the point determined by the two coordinates. Areas with approximate equal numbers of cases were outlined on the chart and the average values of the minimum temperatures within these areas computed. Isolines of minimum temperature were then fitted to these average values for 5° intervals (see fig. 6).

The 700-mb. index temperature and the sum of the current minimum and the average change from figure 5 were then used as coordinates of a second scatter diagram with the observed minimum again plotted in the body of the chart. A similar analysis was made of this chart as shown in figure 7.

For each case estimates of the minimum temperature were obtained from the isolines of figures 6 and 7. These two estimates were then used as coordinates of a third scatter diagram and the observed minimum temperature again plotted. The same analysis was made on this chart and isolines of minimum temperatures drawn (fig. 8). An estimate from figure 8 gives the final forecast of the minimum temperature.

While sets of curved lines were drawn on figures 6 and 7, the more or less even spacing of the lines and the relatively slight curvature suggest that perhaps the true relationships are linear. A least-squares regression equation of the following form was therefore computed:

$$Y=aX_1+bX_2+cX_3+dX_4+e$$

where Y=the verification minimum temperature

X_1=the maximum temperature

X_2=the surface index temperature

X_3=the current minimum plus the estimated change from figure 5.

X_4=the 700-mb. index temperature

The constants a, b, c, d, and e were evaluated, which resulted in the following equation for forecasting the minimum temperature, Y:

$$Y=.35X_1+.19X_2+.24X_3+.37X_4-.75$$

The multiple correlation of the four variables with the verification minimum temperature was .92. The results obtained by using the equation to forecast the minimum temperature were very similar to those obtained from the charts, but the chart results seem to have a very slight advantage both in the average error and the extreme errors made, both in the original data and the test data (historical). (See below.)

The graphical technique has the advantage that no assumptions whatever need be made about the relationships between the independent variables and the dependent variable. In this particular case the assumption of linearity will probably prove to be true in the long run, but in other forecast problems such an assumption might well lead to very erroneous results. In general in using the graphical technique of combining variables it is better to draw the isopleths most consistent with the data on the chart, and make no assumptions whatever. Another advantage of the graphical technique over regression equations that should be considered is that the analysis can be made without recourse to a calculating machine, while the computation of a five variable regression equation without a modern calculator would be laborious indeed.

RESULTS

Three years of winter months were used for developmental or original data upon which the charts were based. These data included January, February and March of 1948-49-50 (271 cases). For test purposes the months of January, February, March, and December of 1947, December 1950, January, and February of 1951 were utilized (209 cases). (Charts for February 28 and March 1, 1947 were missing.) These data will be referred to as test data (historical). The system has been in use in day-to-day forecasting beginning in March 1951, so a very practical day-to-day test on ten additional months has been possible. The months are March and December 1951, January, February, March, November, and December 1952, January, February, and March 1953. These data will be referred to as test data (current).

TABLE 1.—*Comparison, on basis of average error, of Objective forecasts using charts, Objective forecasts using regression equation, and Official forecasts. Original data (271 cases)*

Month	Average error: Objective forecasts using charts	Average error: Objective forecasts using regression equation	Average error: Official minimum temperature forecasts
	° F.	° F.	° F.
1948: January	4.3	4.5	4.8
February	4.2	4.3	5.2
March	3.9	4.5	5.4
1949: January	5.3	4.9	5.7
February	3.1	3.7	5.0
March	3.3	3.5	3.5
1950: January	4.3	7.6	7.0
February	2.9	3.2	3.8
March	3.2	4.0	4.3
All months	3.8	4.5	5.0

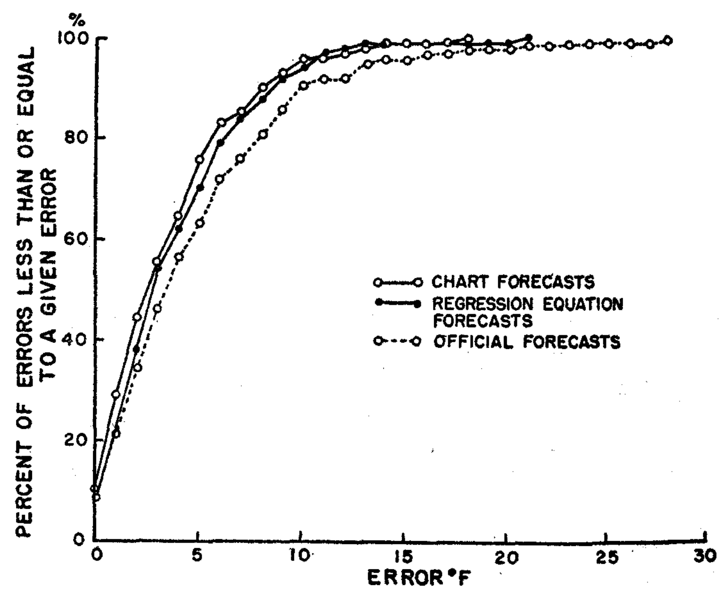

FIGURE 9.—Cumulative frequency distributions of errors for Objective system forecasts using charts, Objective system forecasts using the regression equation, and Official forecasts. Original data (271 cases).

Original Data. A comparison was made on the original data between the results obtained when the charts were used and the results when the regression equation was used to make the forecast. This comparison is presented in table 1 on the basis of average error by months. In this table the average errors of the official minimum temperature forecasts are also listed. The official forecast is the one issued at approximately 0800 MST for the following night. This forecast is generally presented as a 6° range of temperature and for comparison purposes, the forecast temperature was taken as the middle of the range. For example, a forecast of 20°–25° F. was considered a forecast of 23°.

Figure 9 shows cumulative distribution curves of the errors for the three sets of forecasts. The chart forecasts show a consistently higher percent of errors less than or equal to any given error that the official forecasts show.

Test Data (*historical*). All forecasts from test data were made using the official maximum temperature forecasts. The same analysis of errors was made for these seven months of test data as described above for the original data. Table 2 shows the average errors for the three sets of forecasts. The average errors for all seven months are practically identical and in only two individual months is there an appreciable difference between the chart forecasts and the official forecasts, one in which the objective system was better and one in which the official forecasts were better. The cumulative frequency curves of errors in figure 10 are also very similar and show no significant differences, except that the regression equation forecasts have the largest extreme error.

Test Data (*current*). The objective forecasts were computed only from the charts when the system was put into daily use since the chart forecasts consistently showed a slight advantage over the regression equation forecasts in both the original and test data (historical). A similar summarization of results as described above was made of the day-to-day test data. The summarization has been made by seasons, however, to try to discover if there has been any apparent increase in accuracy, on the average, since the aid has been in use. Tables 3 and 4 show the average errors for the two seasons and figures 11 and 12 the cumulative frequency curves of errors.

In the first season the forecasts are practically identical, with the objective forecasts perhaps having a slight edge, whereas in the second season the official forecasts consistently have the better forecasts, on the average. This might well be attributed to the forecasters being more familiar with the objective system, especially with its shortcomings and where it is likely to "bust," and thus, on the average, are able to improve upon the objective indication of the forecast. If this were true, the official forecasts should show progressive improvement from the period

TABLE 2. *Comparison, on basis of average error, of Objective forecasts using charts, Objective forecasts using regression equation, and Official forecasts. Test data (historical) (209 cases)*

Month	Average Error		
	Objective forecasts using charts	Objective forecasts using regression equation	Official minimum temperature forecasts
	°F.	°F.	°F.
1947: January	5.0	5.2	4.7
February	5.5	6.0	5.7
March	3.8	3.7	3.8
December	4.9	5.1	3.9
1950: December	4.8	4.8	4.5
1951: January	5.8	6.6	7.4
February	5.8	6.0	5.5
All months	5.1	5.3	5.1

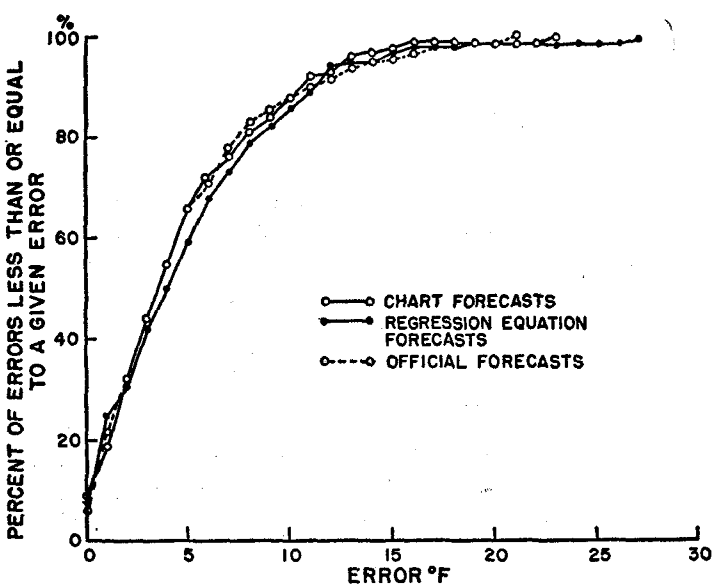

FIGURE 10.—Cumulative frequency distributions of errors for Objective forecasts using charts, Objective forecasts using the regression equation, and Official forecasts. Test data (historical) (209 cases).

TABLE 3.—*Comparison, on basis of average errors, of Objective forecasts (charts) and Official forecasts. Test data (current) first season objective aid was used. (153 cases)*

Month	Average error	
	Objective forecasts	Official forecasts
	°F	°F
Mar. 1951	4.6	5.5
Dec.	5.5	6.0
Jan. 1952	4.1	4.0
Feb.	3.2	3.2
Mar.	3.6	3.6
All months	4.2	4.4

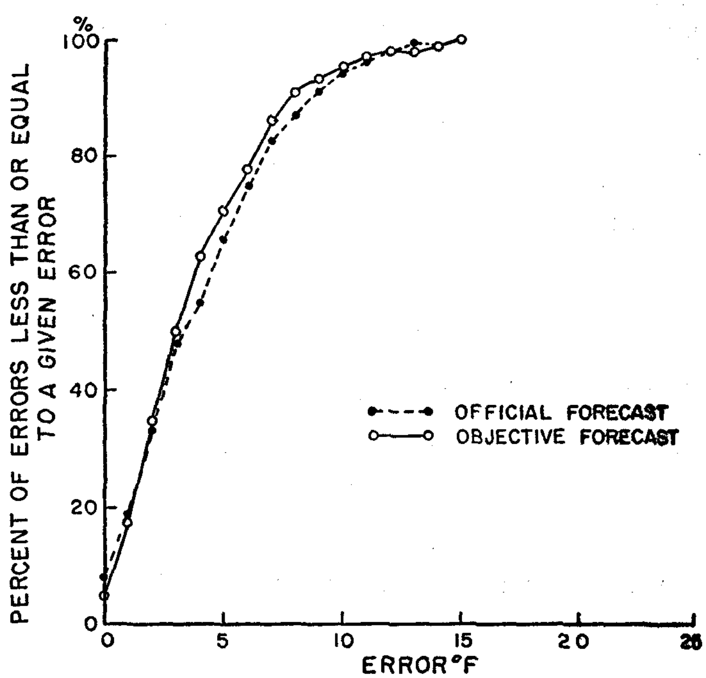

FIGURE 11.—Cumulative frequency distributions of errors for Objective forecasts (charts) and Official forecasts. Test data (current) first season objective aid was used (153 cases).

TABLE 4.—*Comparison, on basis of average errors, of Objective forecasts (charts) and Official forecasts. Test data (current) second season objective aid was used. (151 cases)*

Month	Average error	
	Objective forecasts	Official forecasts
	°F	°F
Nov. 1952	4.8	3.9
Dec	3.8	3.8
Jan. 1953	6.2	6.0
Feb	4.4	3.4
Mar	3.4	3.0
All months	4.5	4.0

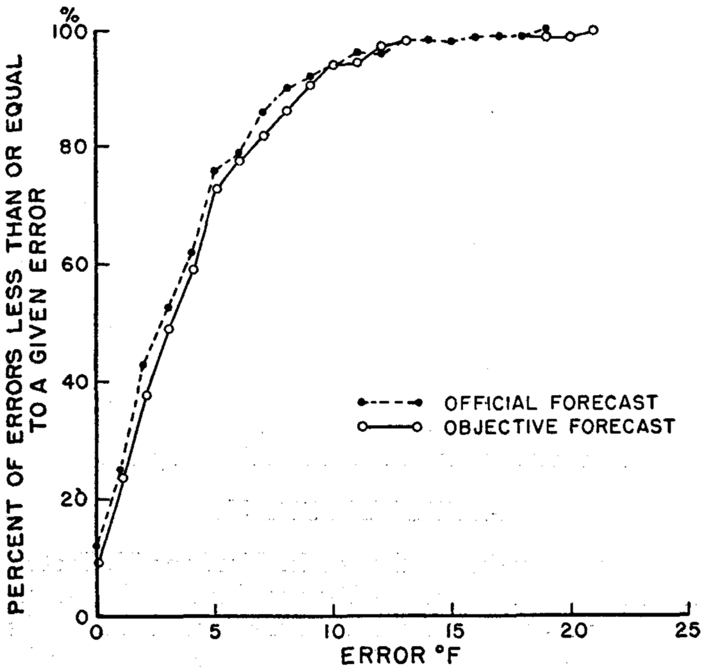

FIGURE 12.—Cumulative frequency distributions of errors for Objective forecasts (charts) and Official forecasts. Test data (current) second season objective aid was used (151 cases).

the aid was put in use through the two seasons when the aid was used. This does show up in the average error, as shown below, but more strikingly in the cumulative frequency distributions of errors as shown in figure 13.

	Average error	*Average change in minimum temperature*
Period before aid was available (original data and test data, historical, 18 months)	5.0	7.5
1st season aid was available	4.4	6.2
2nd season aid was available	4.0	6.4

To offset this evidence of improved accuracy is the fact that the average change in minimum temperature (and presumably the average difficulty of the forecast) was greater during the period before the aid was available, as shown above. Another weakness of the analysis is the fact that the period before the aid was available includes almost four times as many months as either of the seasons when the aid was available. While there is some evidence

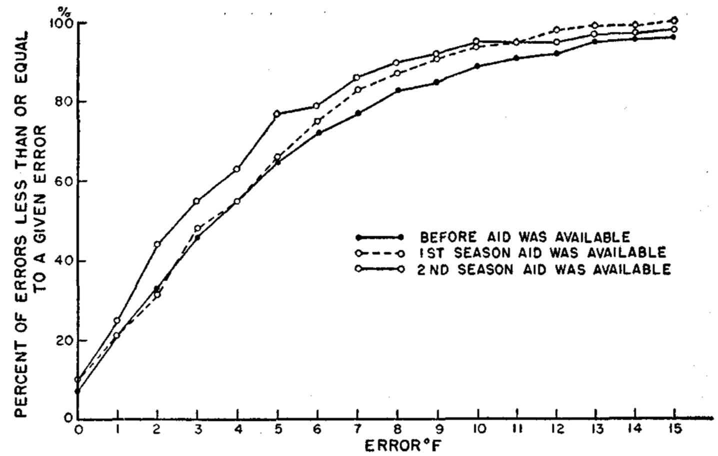

FIGURE 13.—Cumulative frequency distributions of errors for Official forecasts for three periods of time: (1) Before objective aid was available, 18 months; (2) first season aid was available, 5 months; and (3) second season aid was available, 5 months.

that the aid has contributed to an increase in accuracy, at least two more seasons of use will be needed to draw any definite conclusions.

SOURCES OF ERROR

There are certain obvious sources which contribute to errors in minimum temperature forecasting. Factors such as amount of cloud cover during the day and night, condition of the ground, snow cover, wind direction, and wind speed are of undisputed importance in determining the final minimum temperature which occurs, but from a practical standpoint for a long period forecast these factors themselves must be forecast if their effects upon the temperature are to be taken into account in the final forecast. Since the forecast of these factors is subject to considerable error, and since their effects upon the final reading of the minimum temperature are not known quantitatively the net result is the creation of a maximum accuracy that can be expected in forecasting the minimum temperature which is several degrees removed from a zero error.

There are several sources of possible failure of the system due to assumptions made in developing the system and due to the fact that a method of this kind tends to forecast "average" situations and the unusual situation is only partially accounted for, and sometimes entirely unaccounted for. Several situations which have been noted in the use of the system that apparently account for some of the larger errors are described below. These are separated into two groups, (1) Correct Trend, but forecast change too small, and (2) Incorrect Trend, with resulting large error.

(1) Correct Trend.

(a) On rare occasions the temperature "tomorrow morning" at Denver will be colder than any temperature reported to the north in Wyoming, or even Montana "this morning". This results from a snow situation which deposits a fairly heavy amount of snow in the Denver area during the day followed by rapid clearing in the early evening. The system will forecast the correct trend in temperature under these conditions, but the combination of snow and clear skies results in a much lower temperature than is forecast. *If* the forecaster can forecast this combination of circumstances correctly a large error may be avoided.

(b) In the opposite sense, when a warming trend is forecast, a strong chinook or downslope wind may blow the entire night maintaining unusually warm temperatures. The chinook wind is a result of the development of a surface "lee" trough east of the mountains with very strong west winds aloft from immediately above the surface to 20,000 feet or higher. Whether or not these strong winds will break through the normal nighttime inversion is a very difficult forecast problem. Peculiar and very erratic temperature fluctuations can occur under such conditions [12].

(2) Incorrect Trend. There are several situations which can result in an incorrect trend indication from the variables used.

(a) Low pressure system to the west of Sheridan, when Sheridan is under the influence of a shallow surge of cold air from the north. In these cases the rising pressure trend at Sheridan sometimes results in a falling temperature forecast which fails to verify. In this situation the cold air that has pushed into the Sheridan area is generally quite shallow and the low pressure from the west takes over resulting in a falling pressure trend after the 0530 MST chart. The pressure rise is shunted eastward over the Dakotas and does not affect the Denver area.

(b) Rapidly moving surges of cold air from Canada. The assumption that Sheridan will be in the cold air 24 hours prior to Denver will not always hold. In this situation the cold air with rising pressure is sometimes just north of the Sheridan area on the 0530 MST chart and 24 hours later the surge is south of Denver. In these cases Sheridan has a falling 12-hour pressure change and the temperature trend usually falls in category I, or the warmer trend, resulting in a "bust" forecast.

(c) Well-defined storms over the North Central States. In this synoptic situation the 12-hour pressure change at Sheridan is a rising one and a high pressure area is pushing into the Sheridan area. With the rising pressure trend at Sheridan, the temperature trend from figure 3 or 5 is usually in category III or falling trend. This sometimes fails to verify, especially to the limits that the system specifies, because the main surge of the cold air is drawn eastward into the storm over the North Central States.

(d) Closed Lows aloft that stagnate west of the Divide. In these cases the temperature trend from the surface indications is generally of the category III type which calls for colder temperatures. The system assumes movement of these Lows which would bring cold air over the Denver region, but if the Low remains stationary the cold air will be delayed in reaching Denver until the Low moves eastward. A correct forecast of the movement, or stagnation, of such Lows obviously would aid in eliminating extreme errors in these cases.

(e) Rapidly falling pressure at Grand Junction and lesser falls at Sheridan. This results in the temperature trend falling in category III, calling for colder temperatures when sometimes there is actually no source of colder air coming into the area. This situation does not result in extreme errors, but may result in errors of 6° to 10° F.

CONCLUSIONS

The relatively simple method for forecasting the minimum temperature at Denver 24 hours in advance outlined in this paper has been shown to produce forecasts of comparable accuracy to those that have been issued for the past several winters. There are undoubtedly times when the experienced forecaster will recognize that the variables used are inadequate and may lead to an extremely erroneous forecast. It is hoped that with continued use of the aid and greater familiarity with its shortcomings the forecasters will be able to consistently improve upon the forecast produced by the aid and thus in the long run improve the overall skill in forecasting the minimum temperature for Denver. There is some evidence, based on the two seasons during which the aid has been in use, that this goal is being achieved, but several more seasons will be required before a definite conclusion on this point may be reached.

ACKNOWLEDGMENTS

The author wishes to thank Mr. Woodrow W. Dickey, Research Forecaster at the Denver Forecast Center, for his help and guidance throughout the development of the aid and preparation of this paper. The help given by Virginia Reynolds, Research Assistant, in the collection of data and copying of diagrams and charts is also greatly appreciated.

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